

Comment on "Three-dimensional hydrodynamic simulations of the combustion of a neutron star into a quark star"

M. I. Krivoruchenko and B. V. Martemyanov

Institute for Theoretical and Experimental Physics, B. Cheremushkinskaya 25
117218 Moscow, Russia

Abstract

If strange matter is absolutely stable, the ordinary nuclei decay to strangelets, while neutron stars convert into strange stars. Lifetimes of the ordinary nuclei are constrained experimentally to be above $\sim 10^{33}$ years, while lifetimes of the metastable neutron stars depend on the neutron star masses and can exceed the age of the Universe. As a consequence, the neutron stars and the strange stars can coexist in the Universe. We point out that numerical simulations of the conversion of neutron stars to strange stars, performed by M. Herzog and F. K. Röpke in Phys. Rev. D **84**, 083002 (2011), are focused on a region in the parameter space of strange matter, in which low-mass neutron stars and strange stars are coexistent, whereas massive neutron stars are highly unstable and short lived on an astronomical timescale.

In 1960 Ambartsumyan and Saakyan¹ pointed out that production of hyperons becomes energetically favorable inside neutron stars and calculated the composition and the equation of state (EoS) of cold baryonic matter. The existence of quark stars was conjectured by Ivanenko and Kurdgelaidze.² Quark stars whose interior consists of strange quark matter (SQM) were discussed by Itoh in 1970.³ The next year Bodmer⁴ discussed the possible existence of absolutely stable SQM, the binding energy of which at zero external pressure could be greater than that of ordinary nuclei. This idea has attracted interest only much later, after the publication of Witten's (1984) seminal paper.⁵ Detailed calculations in the framework of the MIT bag model, made by Farhi and Jaffe,⁶ confirmed that for an admissible range of parameters the SQM is bound.

Existence of the absolutely stable SQM does not contradict to the fact that ordinary nuclei are composed of nucleons. The critical density of the phase transitions with conservation and non-conservation of strangeness, i.e., with turned off and turned on weak interaction, differ only by a numerical factor, so the bound SQM automatically implies that critical density of the phase transition with the conservation of strangeness is relatively low.

At the saturation density, the nuclear matter is still in the baryonic phase. From this condition, Farhi and Jaffe⁶ derived a restriction on the binding energy of the SQM and the vacuum pressure B . For the quark-gluon coupling constant $\alpha_c = 0$ and the strange quark mass $m_s = 100$ MeV they found $E/A > m_N - 90$ MeV, where m_N is nucleon mass, and

$$B^{1/4} > 145 \text{ MeV. (stability of nuclei)} \quad (1)$$

Stronger constraints follow from the existence of neutron stars. If SQM is absolutely stable, the phase transition to quark matter with the conservation of strangeness leads, on a weak interaction time scale, to the conversion of quark matter to SQM and the eventual slow (deflagration) or fast conversion of a neutron star into a strange star. Such a process is followed by neutrino burst, which can be detected by terrestrial observatories. Neutrino bursts accompanying the slow combustion of neutron stars into quark stars can have duration up to 5 min. with average neutrino energy of a few MeV.⁷ 1-minute intervals on the historical data were analyzed at the Baksan scintillation telescope⁸; no statistically significant excess of neutrino events was found. 10-second signals are expected from supernova explosions and also from the conversion of neutron stars into quark stars in the scenarios in which the phase transition leads to gravitational instability.⁹ Given that neutrino signal is not confirmed by an observation of supernova in optics, x-rays or gamma rays, in-depth analysis of neutrino spectrum and the time evolution of the signal is required to discriminate between scenarios. In this respect, the long-duration neutrino signals provide a cleaner signature for the identification of "quark-novae". 10-second intervals were analyzed at the Sudbury Neutrino Observatory,¹⁰ also with zero result.

If the conjecture on the absolutely stable SQM is correct, then all compact stars are either neutron stars or strange stars. The neutron stars are metastable with respect to conversion to strange stars, and their central density is lower than the critical density of the phase transition with the conservation of strangeness.

In observational astrophysics, there are ample indications that compact objects are neutron stars rather than strange stars. The existence of neutron stars provides stronger constraints on the parameters of the MIT bag model, compatible with the absolutely stable SQM. These constraints can be further improved by considering conditions inside newly born hot protoneutron stars during the first seconds after the core collapse supernovae. Such limits are derived in Refs.^{9,11,12} For $\alpha_c = 0$, e.g., the absence of phase transition with the conservation of strangeness inside a protoneutron star with the baryon rest mass of $1.4 M_\odot$ implies

$$B^{1/4} > 155 \text{ MeV. (stability of neutron stars)} \quad (2)$$

In recent years, pulsars with masses $\sim 2.0 M_\odot$ have been reported.^{13,14} Such pulsars, if they are neutron stars, have a high central density and more favorable conditions for conversion into strange stars. A neutron star with mass $\sim 2.0 M_\odot$ rules out three softest EoS of nuclear matter out of the six ones examined in Refs.^{11,12} The stiff EoS^{15,16,17} still do not contradict the absolutely stable SQM, although its binding energy must be small. For $\alpha_c = 0$ and $m_s = 100$ MeV, the binding energy of less than 30 MeV is allowed in the model of Baron, Cooperstein and Kahana,¹⁵ while in the models of Pandharipande and Smith^{16,17} the SQM is, for this particular choice of parameters, unbound.

An evidence that SQM is unbound comes from the relatively high crossover temperature of QCD. The absolutely stable SQM requires for two-flavor quark matter $T_c(n_f = 2) < 122 \pm 7$ MeV,²¹ whereas numerous lattice data give $T_c(n_f = 2) = 175 \pm 10$ MeV.²²

It is presently unknown whether strange stars exist at all. On the other hand, it has been discussed whether there do exist undoubted observable indications that at least some of the compact stars are not strange stars.^{18,19,20} The constraints of Refs.^{9,11,12} are valid provided one can find in the Universe at least one neutron star with a mass above $1.4 M_\odot$.

In Ref.²³ results of the numerical simulation of combustion of a neutron star into a strange star are reported. The conversion to the absolutely stable SQM is found to be turbulent for a substantial part of the parameter space of the MIT bag model. This interesting analysis oversteps the line of the coexistence of massive neutron stars and strange stars:

Given a neutron star of mass $1.4 M_\odot$, the horizontal lines in Figs. 1 and 2 of Ref.²³ should be moved up to the level of 155 MeV. The left two-thirds of Fig. 3, four out of the five rows of Table 3, three of the four curves in Fig. 4, all the Fig. 5, four of the six columns of Table 2, four of the five curves in Fig. 6, all the Fig. 7, and Sections 5B and 5C are also excluded.

Almost all scenarios described in Ref.²³ belong to a universe without the massive neutron stars.

During the time that has elapsed since the publications of Bodmer⁴ and Witten,⁵ there arose a disagreement with lattice models concerning crossover temperature of QCD, while experimental searches for stable strange matter in the laboratory and astrophysics did not yield positive results. Nevertheless, strange quark matter still deserves careful study, for it has important physical implications. A strong argument in favor of the existence of strange quark matter would be the observation of a long-duration soft neutrino burst accompanying combustion of a neutron star into a quark star. Observation of two pulsars with equal masses and different radii would provide an indirect evidence for coexistence of neutron stars and strange stars. Another point worth noting is that since low-mass strange stars are bound by the strong force, their rotation speed is not constrained by the Kepler frequency. A period of rotation $\lesssim 0.5$ milliseconds would indicate a low-mass strange star. Eventually, one can hope that fast progress in lattice gauge theories on their part will help to also describe quantitatively cold baryonic matter.

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